Mon. Not. R. Astron. Soc. **000**, 1–4 (2007) Printed 31 March 2009 (MN LaTeX style file v2.2)

Constraining white-dwarf kicks in globular clusters : III. Cluster Heating

Jeremy Heyl[1]
[1] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada, V6T 1Z1*
Email: heyl@phas.ubc.ca; Canada Research Chair

31 March 2009

ABSTRACT

Recent observations of white dwarfs in globular clusters indicate that these stars may get a velocity kick during their time as giants. This velocity kick could originate naturally if the mass loss while on the asymptotic giant branch is slightly asymmetric. The kicks may be large enough to dramatically change the radial distribution of young white dwarfs, giving them larger energies than other stars in the cluster. As these energetic white dwarfs travel through the cluster they can impart their excess energy on the other stars in the cluster. This new heat source for globular clusters is expected to be largest during the clusters' youth.

Key words: white dwarfs — stars : AGB and post-AGB — globular clusters : general – stars: mass loss — stars: winds, outflows

1 INTRODUCTION

Spruit (1998) proposed that white dwarfs can acquire their observed rotation rates from mild kicks generated by asymmetric and off-centered winds toward the end of their time on the asymptotic giant branch (AGB) (Vassiliadis & Wood 1993). Fellhauer et al. (2003) invoked these mild kicks to explain a putative dearth of white dwarfs in open clusters (e.g. Weidemann 1977; Kalirai et al. 2001). Davis et al. (2008) observed a possible signature of white-dwarf kicks in NGC 6397, and Calamida et al. (2007) found similar but weaker hints in Omega Centauri. Davis et al. (2008) found that young white dwarfs are less centrally concentrated than either their progenitors near the top of the main sequence or older white dwarfs whose velocity distribution has had a chance to relax.

Early in the life of a cluster mass loss due to stellar evolution competes with the loss of stars due to evaporation from the cluster (Spitzer 1987). Without a kick young white dwarfs would have a velocity distribution nearly equal to that of their more massive progenitors on the main sequence. In this case the kinetic energy of these white dwarfs is much less than equipartition; therefore, as their velocity distribution relaxes they cool the rest of the cluster. If on the other hand white dwarfs receive a substantial kick at birth as observations indicate (Davis et al. 2008), young white dwarfs may heat the rest of the stars in the cluster. This letter will examine how white dwarf kicks affect the energy balance within a globular cluster.

2 CALCULATIONS

Clusters of stars can typically be modelled with a lowered isothermal profile (or King model) (Michie 1963; King 1966; Binney & Tremaine 1987).

$$f = \frac{\mathrm{d}N}{\mathrm{d}^3x\mathrm{d}^3p} = \begin{cases} \rho_1(2\pi\sigma^2)^{-3/2}\left(e^{\epsilon/\sigma^2}-1\right) & \text{if } \epsilon > 0 \\ 0 & \text{if } \epsilon \leqslant 0 \end{cases} \quad (1)$$

where $\epsilon = \Psi - \frac{1}{2}v^2$ and Ψ is the gravitational potential. Because the distribution function depends only on constants of the motion (the energy), it is constant in time as well.

With time the kinetic energy within the cluster approaches equipartition between the various stars such that $m_i\sigma_i^2 = m_j\sigma_j^2$ (Spitzer 1987). The progenitors of young white dwarfs will be the most massive main-sequence stars in a cluster at the time, so they will typically have $\sigma_{\rm TO} < \sigma_{\rm cluster}$, where $\sigma_{\rm cluster}$ is the mean velocity dispersion of the cluster. As these stars evolve they lose mass. During a globular cluster's youth, this stellar mass loss dominates the mass loss from

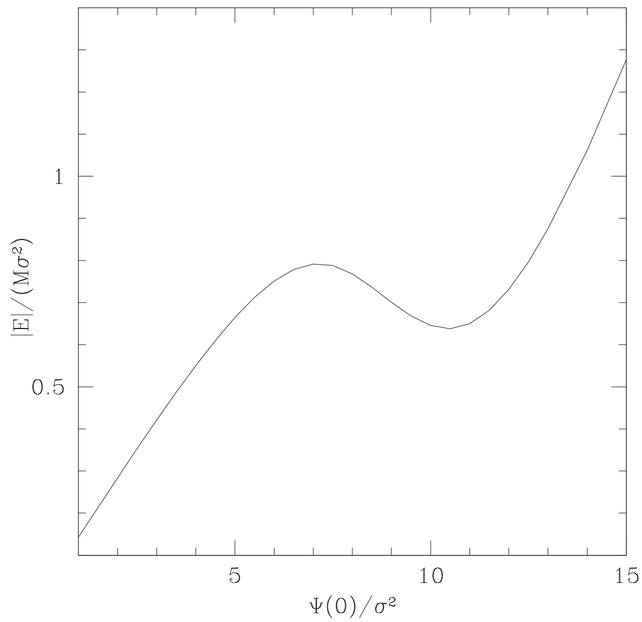

Figure 1. The total binding energy of a cluster modelled with a lowered isothermal distribution function as a function of the central gravitational potential. For small $\Phi(0)$, the total binding energy increases linearly with the central potential. For large values of $\Phi(0)$, $|E| \propto \Phi(0)^2$.

the cluster; later the relaxation of the stellar velocity distribution to a Maxwellian and the subsequent evaporation of stars from the cluster dominates.

2.1 Kicks

At middle age the mass of white dwarfs that remain in the cluster may exceed a third of the total mass of the cluster; consequently, if white dwarfs receive a kick comparable to the velocity dispersion of the cluster (Davis et al. 2008; Heyl 2007a, 2008), the total kinetic energy of the kicks may approach 10-20% of the binding energy of the cluster as shown in Fig. 1.

Specifically, Heyl (2008) found that an initial distribution of white-dwarf progenitors with $\sigma_{\rm TO} = 0.5\sigma$ and a typical kick velocity of $\sigma_k = 1.84\sigma_{\rm TO}$ could explain the observations (Davis et al. 2008). Essentially, young white dwarfs receive a kick of the same order as the velocity dispersion of the cluster. Furthermore, unlike neutron stars whose kicks nearly always cause them to leave the cluster, most of the young white dwarfs remain in the cluster to heat it up (only about two percent escape within a crossing time).

These results provide an estimate of the total power in white-dwarf kicks,

$$\frac{\epsilon_{\rm kick}\tau}{M\sigma^2} \approx \frac{\zeta}{2} \left| \frac{d\ln N}{d\ln m} \left(\frac{d\ln\tau}{d\ln m} \right)^{-1} \right|_{m=m_{\rm TO}} \frac{0.38{\rm M}_\odot + 0.15 m_{\rm TO}}{\bar{m}} \quad (2)$$

where dN/dm is the number of stars per unit mass in the cluster (the mass function), M is the total mass of stars in the cluster, $\bar{m}$ is the mean mass of stars in the cluster, $\tau(m)$ is the duration of the main sequence for a star in the cluster, $\tau = \tau(m_{\rm TO})$ (the age of the cluster), and $\zeta = (v_{\rm kick}/\sigma)^2 \approx 0.85$. Iben & Renzini (1983) give the initial-final mass relation in the numerator of the rightmost expression.

Richer et al. (2007) estimate the current mass function for a region near the half-light radius of NGC 6397 to be

$$\frac{dN}{dm} = Am^{-\alpha}, \frac{d\ln N}{d\ln m} = 1 - \alpha \quad (3)$$

where the slope of the mass function today is given by $\alpha = 0.13$ and $m_{\rm TO} \approx 0.8{\rm M}_\odot$ ($\tau_0 \approx 12$ Gyr is the current age of the cluster) and $d\ln\tau/d\ln m \approx -3.75$ (Straniero & Chieffi 1991) for a cluster of the age and metallicity of NGC 6397.

Integrating Eq. (3) over the masses of the stars in the cluster gives the mean mass of a star in the cluster (assuming $\alpha < 1$ and $m_{\rm TO} \gg m_{\rm min}$, the minimum mass of a star),

$$\bar{m} = \frac{1-\alpha}{2-\alpha} m_{\rm TO} \approx 0.37{\rm M}_\odot \quad (4)$$

so

$$\frac{\epsilon_{\rm kick}\tau}{M\sigma^2} \approx \frac{\zeta}{2}\frac{2-\alpha}{\beta}\left(\frac{0.38{\rm M}_\odot}{m_{\rm TO}} + 0.15\right) \approx 0.13 \quad (5)$$

for the current observations of NGC 6397.

2.2 Binaries

In a binary a fraction of the energy of the kick is used to change the orbital parameters (Heyl 2007b). If the masses of the primary and secondary are similar due to dynamical biasing (e.g. McDonald & Clarke 1993), the total kick to the binary is about 70-80% of the kick imparted to a single star, so given that the fraction of binaries is small in the cluster as a whole and the correction to the kick for binaries is also small, the energetics of changing the orbits of binaries will be ignored.

On the other hand, the binaries provide an important energy source for the cluster (in fact the only energy source if one excludes the kicks). The interaction of a binary with a single star can result in an exchange or the dissolution of the binary, but generally it results in an increase in the kinetic energy of final single star (like a kick) at the expense of the increased binding energy of the binary. The velocity increment of the singleton is generally random (also like a kick), so these two energy sources are similar and possibly comparably important to the evolution of the cluster.

Spitzer (1987) gives an estimate for the power from binaries of

$$\epsilon_{\rm binary} t_r \approx \frac{0.92}{\ln\Lambda} N_b \frac{\bar{m}\sigma^2}{2} \quad (6)$$

per relaxation time,

$$t_r \approx \frac{\sigma^3}{1.22 n_s 4\pi G^2 \bar{m}^2 \ln\Lambda}. \quad (7)$$

where N_b is the number of binaries. Combining these results yields

$$\frac{\epsilon_{\rm binary}\tau}{M\sigma^2} \approx 7.1 n_b \left(\frac{G\bar{m}}{\sigma}\right)^2 \sigma\tau \quad (8)$$

$$\approx 0.22 \left(\frac{\bar{m}}{0.37{\rm M}_\odot}\right)^2 \frac{n_b}{1{\rm pc}^{-3}} \left(\frac{1\ {\rm kms}^{-1}}{\sigma}\right)^3 \frac{\tau}{12\ {\rm Gyr}}. \quad (9)$$

where the binary fraction is taken to be around a few percent suitable for a typical region of the cluster outside the core (Davis et al. 2008). The power produced by the binaries is of course proportional to the number density of the binaries and inversely proportional to the velocity dispersion that sets the cross-section per binary.

Comparing Eq. (8) to (5) shows that the power sources are similar for the region of NGC 6397 observed by Richer et al. (2007).

2.3 Evolution

To look at the relative importance of binaries and kicks early in the life of the cluster, some assumptions about the mass function of the cluster in the past are needed. First, the mass function becomes more and more top heavy with time as the low mass stars are lost from the cluster; therefore, it is natural to assume that $\alpha > 1$ in the past and possibly $\alpha > 2$ near the turnoff. In this regime, the derivation of Eq. (5) is not valid. The result in general is

$$\frac{\epsilon_{\rm kick}\tau}{M\sigma^2} \approx \frac{\zeta}{2}\frac{|1-\alpha|}{\beta}\frac{0.38{\rm M}_\odot + 0.15 m_{\rm TO}}{\bar{m}} \sim (0.5-1)\,\zeta \quad (10)$$

where the various slopes are evaluated at the turn-off. Using the IMF of Kroupa et al. (1993) below one solar mass and Scalo (1986) above gives $|1-\alpha| \approx 1.7$ compared to $2-\alpha \approx 1.9$ currently. Also the value of the β only changes with time slightly (for $m_{\rm TO} \sim 1{\rm M}_\odot$, $\beta \approx 3$), so the bulk of the increase comes from the replacement of the turn-off mass with the mean mass in the denominator of the expression.

Of course as the cluster evolves, the velocity dispersion of the cluster should also evolve. Because the mass of the cluster was larger in the past, one would expect that the velocity dispersion was also larger. On the other hand, the kick velocity may also change with the turn-off mass, so it is natural to introduce both of these quantities as variables. The power from binaries also depends sensitively on the velocity dispersion and mean stellar mass. Taking the ratio of the kick power to the binary power yields,

$$\frac{\epsilon_{\rm kick}}{\epsilon_{\rm binary}} = 0.07\frac{|1-\alpha|}{\beta}\frac{(0.38{\rm M}_\odot + 0.15 m_{\rm TO})\, v_k^2\sigma}{G^2\bar{m}^3 n_b \tau} \quad (11)$$

$$\approx 40\frac{v_k^2\sigma}{(1\ {\rm kms}^{-1})^3}\frac{1\ {\rm Gyr}}{\tau}\frac{1\ {\rm pc}^{-3}}{n_b} \quad (12)$$

where the approximation holds for $\tau = 10^7 - 10^9$ yr. After about a billion years, one would expect the cluster to have evolved structurally, ejecting many of the low mass stars. This would change the mass function and typically decrease this ratio further. The increased velocity dispersion of the cluster actually increases the relative importance of kicks early in the life of the cluster by increasing the relaxation time (decreasing the binary power). On the other hand, the number density of binaries was likely to be larger in the past than today simply because the number of density of stars was larger then.

3 CONCLUSIONS

Over the life of a globular cluster such as NGC 6397, white-dwarfs kicks may provide a significant energy source. In a region outside the core todayt, kicks provide about about one-half of energy input from binaries. Early in the life of the globular cluster when stars of several solar masses are leaving the main sequence, the white-dwarf kicks may actually dominate over binaries as an energy source; consequently, young globular clusters such as those in starburst galaxies may actually differ structurally from their older peers. Drukier et al. (1992) found that an energy source beyond binaries was required to avoid core collapse in M71; perhaps white dwarf kicks could explain this discrepancy. Regardless, these calculations indicate that further study of the effects of white-dwarf kicks on the dynamics of globular clusters is warranted.

ACKNOWLEDGMENTS

I would like to thank Harvey Richer and Saul Davis for useful discussions and the referee, James Binney, would provided many useful comments. The Natural Sciences and Engineering Research Council of Canada, Canadian Foundation for Innovation and the British Columbia Knowledge Development Fund supported this work. Correspondence and requests for materials should be addressed to heyl@phas.ubc.ca. This research has made use of NASA's Astrophysics Data System Bibliographic Services

REFERENCES

Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton
Calamida A., et al., 2007, ArXiv e-prints, 712
Davis D. S., Richer H. B., Anderson J., Brewer J. P., Hurley J., Kalirai J. S., Rich R. M., Stetson P. B., 2008, Astron. J, 803, accepted astro-ph:0803.0005
Davis D. S., Richer H. B., King I. R., Anderson J., Coffey J., Fahlman G. G., Hurley J., Kalirai J. S., 2008, Monthly Notices, 383, L20
Drukier G. A., Fahlman G. G., Richer H. B., 1992, Astrophys. J, 386, 106
Fellhauer M., Lin D. N. C., Bolte M., Aarseth S. J., Williams K. A., 2003, Astrophys. J Lett, 595, L53

Heyl J. S., 2007a, Monthly Notices, 381, L70
Heyl J. S., 2007b, Monthly Notices, 382, 915
Heyl J. S., 2008, Monthly Notices, 385, 231
Iben Jr. I., Renzini A., 1983, Ann. Rev. Astron. Astrophys., 21, 271
Kalirai J. S., Ventura P., Richer H. B., Fahlman G. G., Durrell P. R., D'Antona F., Marconi G., 2001, Astron. J, 122, 3239
King I. R., 1966, Astron. J, 71, 64
Kroupa P., Tout C. A., Gilmore G., 1993, Monthly Notices, 262, 545
McDonald J. M., Clarke C. J., 1993, Monthly Notices, 262, 800
Michie R. W., 1963, Monthly Notices, 125, 127
Richer H. B., Dotter A., Hurley J., Anderson J., King I., Davis S., Fahlman G. G., Hansen B. M. S., Kalirai J., Paust N., Rich R. M., Shara M. M., 2007, Astron. J, 708, accepted, astro-ph:0708.4030
Scalo J. M., 1986, Fundamentals of Cosmic Physics, 11, 1
Spitzer L., 1987, Dynamical Evolution of Globular Clusters. Princeton Series in Astrophysics, Princeton, Princeton
Spruit H. C., 1998, Astron. Astrophys., 333, 603
Straniero O., Chieffi A., 1991, Astrophys. J Supp, 76, 525
Vassiliadis E., Wood P. R., 1993, Astrophys. J, 413, 641
Weidemann V., 1977, Astron. Astrophys., 59, 411